4.2 Phase Two - Monitoring Plume Generation & Decay

A core objective of this project has been to monitor the growth, movement and decay of sediment plumes developed during marine aggregate dredging operations. Emphasis has been placed on the competent collection of representative field information that will assist to develop and augment realistic modelling techniques using validated data.

Pursuant to these objectives, several programmes of fieldwork have been undertaken. Monitoring of the dredge plumes using chartered survey vessels has been successfully undertaken. Interim results have been published in Conference Proceedings (Hitchcock & Drucker, 1996) and incorporated in Technical Reports (HR Wallingford, 1996).

Herewith are presented the full set of results derived from the field monitoring data obtained to date. Selected ADCP™ transects and profile suites are presented.

4.2.1 Monitoring Methodology

Acoustic Doppler current profiling techniques have existed for military purposes since the late 1970s but have really only become commercially viable within the last 10 years. The techniques have received extensive research and commercial application within the US and Far East, but have only relatively recently become a realistic survey tool available within the UK.

Four highly directional transducers, arranged at 90^{o} in the horizontal and inclined outward at 30^{o} in the vertical (so called 'Janus' configuration), emit acoustic pulses into the water column which are reflected from suspended particulate matter. The measured Doppler shift of the returned echo is used to calculate particle (scatterer) velocity in the direction of each of three beams and, by inference, determine the current velocity components in those directions. The fourth acoustic beam can be used to *'bottom track'* and so calculate the velocity over the ground of the unit, and also for data integrity. Alternatively, unit movement can be input from an external source such as a high precision dGPS system. Both methods were used here. Measurements from the three beams are then combined with the known orientation (by fluxgate compass or gyro input) and horizontal velocity of the profiler, to derive current speed and direction relative to earth co-ordinates. Considerable attention must be paid to calibrating the compass to compensate for local magnetic variation aboard the survey vessel, to avoid inducing potentially large errors in the calculations. Air bubbles will interrupt the two way travel time of the pulse and are known to corrupt the received data.

The received signals are then broken down by 'time gating' into discrete 'bins' of data, each as small as 0.25m vertically with the 1200kHz BroadBand system as used. Each 'ensemble' then recorded consists of up to 30 vertical bins of data, or less in shallower water. Data are not available for the top 3m or bottom 6% of the water column for the configuration used (*c.f.* the RDI 600kHz NarrowBand Doppler profiler which loses data for the bottom 15% of the water depth). The received signals are internally compensated for gross attenuation of the signal which is dependent on water depth (beam spreading), acoustic absorption (temperature and salinity) and reflector attenuation (particle size, shape, density and compressibility).

It was found that a scale of 40-100dB best represented the variation in acoustic backscatter attributable to the dredging operations monitored during August 1995, whilst a scale range of 60-120dB was more suitable for the January 1997 monitoring campaign. The absorption coefficient α was determined as 0.418 (based on frequency of 1200kHz, water temperature of 16^{o}C, pH of 8.0, pressure of 1.0 atmosphere and salinity of 35ppt which is assumed linear near 35ppt and includes magnesium sulphate, boric acid and viscous terms). An echo intensity scale value of 0.43dB per AGC count was used and the speed of sound was computed for each ensemble.

In order to deploy the RDI 1200kHz BroadBand ADCP from the 15m survey vessel chartered on all occasions for the fieldwork campaigns, an over-the-side bracket was designed and built in-house which rigidly held the ADCP transducer unit in such a manner as to be (i) away from significant localised sources of magnetic influence; (ii) vertically positioned under the lifting derrick to be used for the deployment of the sampling equipment; and (iii) aligned exactly fore and aft. The latter point is less important for backscatter observations, but is extremely important for obtaining true-vector current measurements. To overcome potential problems of magnetic interference with the transducer head built-in fluxgate compass, a KVH 316AH external fluxgate compass was interfaced to the Deck Box by RS232C serial communications port A. Repeated and reversing transects in known directions (line of sight with Ministry of Defence Naval compass calibration marks on land) were made. An installed deviation of 2^o on the first and third installations, and better than 1^o on the second installation were observed, and this is further accounted for within the data acquisition software.

At the scale of the investigation, it was considered important to plot the results accurately. All the surveys utilised the commercial survey navigation software "HYDRO" produced by Trimble Navigation International Ltd. The surveys were planned using the Ordnance Survey OSGB36 grid using local transformations calculated for the Licence Area where the work was carried out. A survey quality differential GPS provided a position solution to both PCs with accuracy better than ±5m r.m.s. A dedicated PC was utilised to provide steering plan information for the survey vessel helmsman with a second dedicated PC acquiring and storing the ADCP data, with backup data recorded on tape drive. All equipment is owned and was provided by Coastline Surveys Ltd.

Sufficient personnel are required to operate the survey and ADCP computers whilst simultaneously liasing with the dredge vessels involved, deploying and recovering drogues, and undertaking water temperature, salinity, and sampling casts. Accurate notes of all operations and movements of the survey vessel and the dredgers have proven to be indispensable in accounting for many variations, initially similar in appearance.

The ADCP processor was configured such that each ensemble comprised the average value of four consecutive pings for each of the four transducers. Bin size was 1.0m vertical permitting a theoretical range of 30m water depth at a frequency of 1200kHz. To complete one cycle, and record one ensemble of data, takes approximately 4.5 seconds. The resultant bin size is therefore 1m vertical by 12m horizontal at a survey speed of 5 knots (2.5m/s). At a survey speed of 1 knot the bin size will be 1m vertical by x 2.5m horizontal. Ensembles are recorded continuously throughout the survey period, resulting in a hypothetically available dataset of some 312,000 individual current observations over a 13-hour period, obtained by over one million transducer operations.

For current measurements the data are averaged in the field over a (user-definable) 60 second period for real-time display of velocity magnitudes and directions, and for presentation over 250m horizontal distance. Post processing of the data is possible using different time periods or equipment parameters. For Acoustic Backscatter measurements, instantaneous values of the average of the four beams was used for rapid real-time update.

The intensity of the reflected acoustic pulse can be used as a means of representing the relative concentration of suspended particles. Present research is investigating possible calibration of the system for direct measurement of concentrations, but this is at an early stage and is susceptible to the variability of many instrument parameters including transducer power output (*e.g.* manufacture variation, input voltages) and thermal noise and temperature of the circuitry, in addition to environmental parameters.

Plate 4.2.1 *Coastal survey vessel Wessex Explorer used for the plume monitoring surveys.*

Transects across or along the plume axis using the acoustic backscatter function of the ADCP^{TM} were obtained to generate of suspended solids concentration (SSC) information about the dredging activity in a number of ways:

- successive transects perpendicular to the track of the dredger were made to identify the growth and decay of the plume between each pass of the dredger. This would also identify whether there is any cumulative effect leading to an overall gradual build up of SSC levels

- transects were plotted diagonally downstream across the wake of the dredger, expanding the distance away from the centreline of the plume, so that lateral dispersion and longitudinal excursion and time-based decay (settlement) could be determined

Additionally, detailed current measurements were made by continuously executing transect lines along a predetermined track for a thirteen hour period. One complete circuit was timed to take one hour. Each point on the circuit was therefore observed every hour. Review of the current vector plots indicates in a clear manner the time and variation of changes in direction and velocity of the currents, both areally and vertically (*see* Coastline Surveys Ltd, 1995; for complete dataset).

The 15m survey vessel “Wessex Explorer” (Plate 4.2.1) was equipped with water bottle and pump sampling equipment, optical transmissometers (three of varying range), temperature/salinity probes (two), and an RD Instruments’ 1200kHz BroadBand Vessel Mounted Acoustic Doppler Current Profiler (ADCP™) owned by MMS.

On the successful basis of the results obtained and reported herein, use of a Vessel Mounted ADCP™ is considered to be fundamental to accurate monitoring of the plume generation and decay. Confidence can be applied to the results when considering whether observed SSC obtained by water sampling represent the maximum and minimum conditions existing.

Detailed time records and subsequent analysis of the relative dGPS positions of the survey vessel and dredge vessels at all times enabled correlation of the distance and time function of the plume behaviour.

4.2.2 Owers Bank, August 1995

During August 1995, an extensive field monitoring programme was undertaken at a currently licensed aggregate extraction site off the South Coast of the UK to study the generation and decay of benthic and surface plumes arising from a variety of different dredge vessels employing different dredging techniques. The analysis of results is now largely completed and the principal observations are expressed herein.

The objectives of the monitoring exercise were:

- *to measure background suspended solids concentrations (SSC) prior to commencement of dredging (no dredging took place inside the area within the previous 24 hours). One small dredger worked an area to the south of the monitoring area approximately 12 hours before fieldwork commenced but this was considered not to impinge on the study*

- *to use the ADCP™ in Vessel Mounted configuration to locate the limits of the plumes developed, and identify turbidity maxima and minima as identified by the relative values of the acoustic backscatter*

- *to identify the shape and form of the underwater plumes*

- *to quantify the increase in suspended solids concentrations as a consequence of the dredging operation*

- *to map the dispersion and spread of the plumes away from the dredger including delimiting the point of return to background SSC*

- *to determine the dilution of the plume as a function of time*

The data are presented here representing groups of normal commercial dredging scenarios that were encountered during the survey. Excellent weather conditions and detailed logistical planning enabled different modes of dredging (anchored and trailing), different capacity dredgers (from 2000 tonnes to 5000 tonnes) and different overboard returns methods (over the side discharge and central, underwater discharge) to be investigated.

The plumes arising from three dredge vessels were monitored during normal loading operations. The calm weather conditions enabled safe close-quarters manoeuvring by the survey vessel adjacent to the working dredgers. A combination of ‘all-in’ and screened (stone only) cargoes were loaded by trailer suction and anchor suction techniques over a three day period.

The study was conducted over neap tides to ensure greater accuracy of deployment of the water sampling equipment vertically under the survey vessel. Lower current velocities also enabled closer working by the survey vessel alongside the dredge vessel. Importantly, the plume was expected not to disperse as quickly, therefore enabling more measurements to be made within areas of greater concentrations, for particle size analysis.

4.2.2.1 Tidal Regime

In order to put into context the extent of any plumes identified and monitored, it is essential to have detailed knowledge of the tidal current regime existing at a study site. Information on both tidal conditions during any survey work and peak tidal conditions that may exist are required. Data obtained when considering the extent of plume excursion must be related to the state of tide at the time of monitoring.

During the August 1995 plume tracking, tidal velocity data was also acquired by the ADCP™ used. Immediately following the plume monitoring exercise, a detailed tidal current monitoring exercise was undertaken also using the

ADCP™ to establish peak spring tidal conditions at the site. A software program (VMAP) was developed in-house to interrogate the RDI Transect™ post processing output files, calculate the significant descriptive statistics, and output the results in graphical and current vector map forms.

Peak current velocities encountered at the site were 0.97m/s (west bound ebb tide) direction 258°T and 1.07m/s (east bound flood tide) direction 070°T. Mean tidal velocities were 0.56m/s and 0.72m/s respectively (excluding the slack phases). This compares to measurements obtained during the plume tracking exercise when peak current velocities encountered reached 0.6m/s. Other than for a limited time period around slack water, the current patterns were largely linear. Water depths across the site are approximately 22m.

Separate studies conducted nearby during October 1995 compared Doppler current profiling data acquired here with that of an InterOcean S4 self recording current meter. This proved highly successful with correlation coefficients r = 0.983 (velocity) and r = 0.967 (direction).

Not apparent through the use of a single point current meter, such as the S4, the ADCP™ data showed that there was some reduction in current velocity with depth. Average velocities at 15m depth are within 8% of average surface velocities.

4.2.2.2 General Appearance Of Plume

The surface expression of a freshly generated plume in calm waters is characterised by 'swirls' of dirty froth formed by the turbulence of the overboard returns entering the water surface (Plate 4.2.2.2).

Plate 4.2.2.2 *Surface expression of plume as frothy foam with sheen visible in calm conditions*

The screened reject mixture creates the most amount of froth since this is the greatest volume and velocity. During sea conditions other than flat calm, this is quickly dispersed. The 'froth' may contain some naturally occurring precipitate released from the sediment and/or induced through the turbulent mixing of seawater. It is proposed that a significant component of the surface expression of the plume has biological origins. This is expanded further in Section 4.4 and the attached paper Annex 1.

From the deck of the survey vessel, the visible top several metres of the water column contains upwelling clouds of sediment-laden turbulent water. These may be several metres in diameter. Small shell fragments may be temporarily suspended but these rapidly disperse and settle. There are sometimes significant volumes of entrained air bubbles.

During calm conditions there is occasionally an apparent 'sheen' to the water surface, but not observed in every licence area. It is postulated that such a 'sheen' may be due to the disturbance of small quantities of organic matter naturally present in the seabed sediments.

4.2.2.3 Plume Sampling Results

A total of 162 background and through plume transects were made using the ADCP™ equipment to generate real-time continuous backscatter profiles. Sets of data which clearly discriminate the plume and which have reliable sampling data have been interpreted and are presented here.

Water samples of 0.5 litre, 2.0 litre and 10 litre volume were obtained using an array of remotely operated sample tubes, deployed with pressure transducer (depth indicator) and two suspended solids meters. 145 water samples were taken at varying depths within the plume corresponding to turbidity maxima and minima identified in real-time by the ADCP™. Whilst holding station adjacent to a midwater drogue with surface marker buoy, 20 vertical profiles were also recorded by ADCP™ with simultaneous water sampling and optical measurement of the suspended sediment concentrations.

The majority of water samples were analysed for total solids content. A number were selected for determination of the silt/sands ratio *i.e.* the split between particle sizes greater than and less than 0.063mm. Further, a small number of these samples were analysed by laser diffraction techniques for sandy sediment particle size distribution. The generally low SSC prevented full particle size characterisation of more samples. In expectation of such difficulties, some larger samples were collected: however these still did not contain enough sediment for full analysis.

Correlation of the sediment particle size and concentration records with the records from the infra-red transmissometer mounted adjacent to the sampling array indicated a persistent discrepancy. The ranges of turbidity variations recorded by optical techniques were much less than those determined during the laboratory analysis of the field plume samples. This is considered due to the high sand content, rather than silt, in suspension. Such a restriction is largely dependent on the technique, although different manufacturers of equipment claim suitability over different size ranges (*see, for example, equipment products such as D & A Electronics OBS, WS Ocean TRB-1, Alec Electronics etc.)*.

When considering the concentrations of suspended sediments in the water column plume, it is important to consider whether or not the vessel is steaming with or against the tide. If the latter, the dilution effect will be greater, and hence the apparent concentration lower, than if the vessel is steaming with the tide.

4.2.2.4 Background Conditions

Background suspended solids concentrations were determined prior to the start of survey operations on each day of the monitoring exercise. Observed levels were in the range 3-23mg/l average 14mg/l. Interestingly the sand content (>0.063mm) of these samples varied from 14% to 75%.

4.2.2.5 Plume Generated By The ARCO Severn, 19th August 1995

The ARCO Severn loaded an all-in cargo over a period of 3 hours and 15 minutes from Licence Area 124/1 Zones 1 and 8. The cargo is recorded as 50% stone content (>5mm). Background measurements of SSC varied from 3-10mg/l averaging 7mg/l.

Using the equipment aboard the survey vessel, a number of transects and vertical rapid drop profiles were carried out. 7 vertical sampling profiles were obtained collecting 25 water samples. Table 4.2.2.5 below records the concentrations determined from the subsequent laboratory analysis.

The composite Figure 4.2.2.5a shows the CBP records along with the track of the vessel used during the survey. The relative positions of the survey vessel and dredger are clear. The first transect provides an indication of the care needed when interpreting the CBP data: the record was obtained before dredging or overflow commenced and is solely a result of aeration in the water caused by motion of the vessel (at slow speed) and effects of the propeller. The second transect shows the very similar appearance, soon after dredging has commenced, and is a result of limited overflow of almost clear waters. The series of transects further demonstrates the value in using CBP to assist in delimiting the plume boundaries, and ensuring confident placing and interpretation of water samples.

From Table 4.2.2.5 and Figure 4.2.2.5b it is clear that the Total Suspended Solids Concentration rapidly decreases with distance away from the dredger. Within 300-550m, concentrations are at or near to background conditions. The water sample sediments are predominantly sandy with less than 1-2% silt content. Concentrations of silty sediments (<0.063mm) are less than 25mg/l, and reduce to background limits over similar distances (Hitchcock and Drucker, 1996).

Samples with the highest concentrations of solids were obtained within 200m of the dredger near the end of the loading period when overflow would be nearing maximum solids content (as the level of material in the hopper is near the hopper rim). Total SSC ranged from 1170-1346mg/l, the highest being obtained within several metres of the seabed at 175-200m from the dredger. Total SSC levels at 500-600m from the dredger approximate to but still exceed background levels. This is probably a result of the multiple dredge runs combined with low tidal current flow (thus limiting dispersion) causing a short term intensifying effect.

Water samples taken 15 minutes after the dredging operation ceased showed that Total SSC had returned to background conditions observed at the start of the day.

Figure 4.2.2.5a

Time (BST)	Transect Number	Depth (m)	Distance Astern (m)	Total Concentration (mg/l)	silts (<0.063mm) (mg/l)
17:06	-	0	491	46	n/d
15:33	19AU12	0	300	42	n/d
15:46	19AU15	0	102	96	n/d
15:50	19AU19	0	245	99	n/d
16:40:20	19AU29	4	597	30	n/d
16:40:55	19AU29	8	585	26	n/d
16:41:22	19AU29	12	573	18	n/d
16:41:51	19AU29	16	561	18	n/d
16:42:37	19AU29	18	534	18	n/d
16:42:24	19AU29	18	549	22	n/d
17:10:30	19AU34	4	675	10	n/d
17:11:03	19AU34	8	691	13	n/d
17:11:30	19AU34	12	707	13	n/d
17:12:21	19AU34	18	724	25	n/d
17:12:30	19AU34	18	740	38	n/d
17:56:58	19AU41	4	201	47	n/d
17:57:29	19AU41	8	227	304	0
17:57:51	19AU41	12	248	582	0
17:58:16	19AU41	18	259	613	6
18:38:17	19AU45	4	94	723	7
18:38:52	19AU45	8	111	103	n/d
18:39:18	19AU45	12	138	1170	0
18:39:45	19AU45	16	156	1171	0
18:40:12	19AU45	18	178	1346	13
18:40:28	19AU45	18	194	1225	25

Table 4.2.2.5 *Summary of suspended solids concentrations sampled from the plume developed by the ARCO Severn, 19th August 1995.*

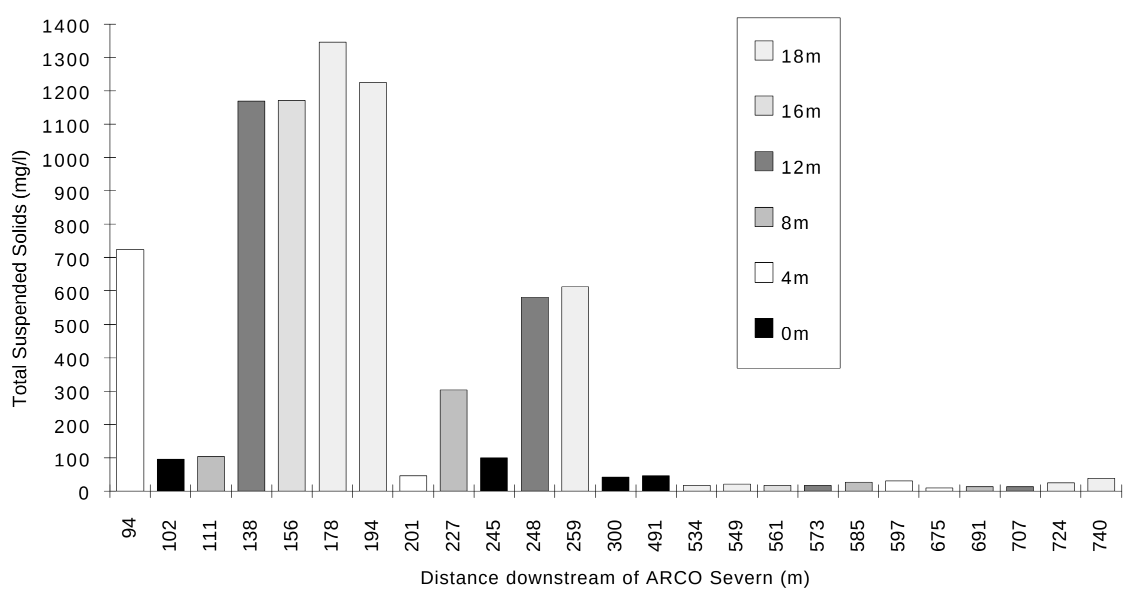


Figure 4.2.2.5b *Total suspended solids concentrations of samples taken from the plume decreasing with distance away from the ARCO Severn, Owers Bank, 19th August 1995.*

4.2.2.6 Plume Generated By The ARCO Severn, 20th August 1995

Background measurements were obtained before dredging commenced within the study area. These were higher than the previous day, averaging 19mg/l. It was noted that a small dredge vessel had been operating on the extremity of the study area overnight, completing the loading immediately prior to the background sampling.

The ARCO Severn loaded a screened stone cargo in the same area as on the previous day (Area 124/1 Zones 1 and 8) taking 3 hours 40 minutes.

Table 4.2.2.6 summarises the plume samples taken. The data suggest that within 800m from the dredge vessel, the majority of the plume had settled to within a few metres of the seabed. This is probably maintained in suspension by turbulent conditions existing within the benthic boundary layer.

Composite Figure 4.2.2.6 presents the CBP records for a series of transects through the ARCO Severn plume taken on the 20th August 1995. The development of the plume and it's subsequent decay is quite clear. The apparent alteration in asymmetry is due to the survey vessel proceeding port to starboard through the plume and then the reverse on successive transects.

Time (BST)	Transect Number	Depth (m)	Distance Astern (m)	Total Concentration (mg/l)	silts (<0.063mm) (mg/l)
11:22:00	20AU13	18	810	25	n/d
11:23:03	20AU13	18	817	61	n/d
11:24	-	0	800	2	n/d
11:25	-	0	820	7	n/d
11:51	-	0	851	5	n/d
16:15	20AU42	18	-	3	n/d
16:27	20AU42	12	-	3	n/d
16:33	20AU42	14	-	4	n/d

Table 4.2.2.6 *Summary of suspended solids concentrations sampled from the plume developed by the ARCO Severn, 20th August 1995*

Recent investigations undertaken off the East Coast of the United Kingdom support the view that the majority of the plume settles very quickly. In addition the observations suggest that there exists a 'benthic boundary layer plume' with suspended sediments at concentrations of the order of 100mg/l (although sample results are not yet available) up to 1m from the seabed which has been located up to 8km from the dredge site (J. Rees, *pers. comm.*). Further results are expected shortly.

Vessel mounted ADCP^{TM} data, obtained during this project does not indicate such a phenomenon. However, the nature of the algorithms used are such that data so close to the seabed is within a 'corruption zone' and is therefore unreliable within this benthic boundary layer. It would be necessary to deploy the ADCP^{TM} in a seabed mounted frame, upward looking, to attempt to track the movement of the plume, although there is a similar, smaller corruption zone at the beginning of the ADCP^{TM} record as well.

We are aware of only one particular form acoustic backscatter sensor designed for such an application. The Aquatec Electronics Ltd. "Acoustic Back Scatter System (ABS)" is a three-frequency sensor in the range 1 MHz to 6 MHz, typically set at 1 MHz, 3 MHz and 6 MHz. The system is designed to measure the sound reflected by sediments at 1cm intervals from the sensor, to a range of 128cm or 256cm. The Acoustic BackScatter System may be used to obtain profiles of suspended sediment concentration and sediment size in the near bed zone and to monitor ripple formation. The Acoustic Back Scatter System has greater sensitivity to coarser, sandy suspensions than optical backscatter systems, which are more sensitive to fine, silty material. Neither instrument establishes the sediment concentration directly, since the relative backscatter is also a function of the grain size and shape. Calibrations may be carried out in laboratory conditions using samples of actual seabed material from the deployment site. Water samples were not collected within 2m of the seabed, to avoid potential damage to the equipment spread.

Samples taken at 1350m from the dredger, located using a mid water drogue as well as visual and ADCP^{TM} techniques, indicate return to background concentrations throughout the water column. Further samples taken 1 hour after completion of dredging operations (16:15-16:33), confirmed that indicate that SSC have returned to background levels within such a time period.

Figure 4.2.2.6

4.2.2.7 Draghead Plume Generated By The ARCO Severn, 20th August 1995

Given that the integrity of ADCP™ data is compromised within the bottom 6% of the water column, it is to be expected that acoustic backscatter observations would be limited. However, we have obtained several transects of good quality which contain good indications of the likely dimensions of the draghead plume.

The resolution of the ADCP™ using a 'bin' size of 1m was adequate to successfully record the benthic plume emanating from the motion of the draghead on the seafloor, approximately 30m astern and downtide of the draghead.

Figure 4.2.2.7 shows a CBP record of the relative acoustic backscatter for this transect. The formation of small plume attributable to the draghead is clearly visible near the seabed, slightly left of centre of the main plume. This is on the port side of the dredge vessel, and corresponds with the beam of the dredger extremely well. A small reject plume can be identified near the sea surface on the starboard side of the vessel, separate from the overspill contributions.

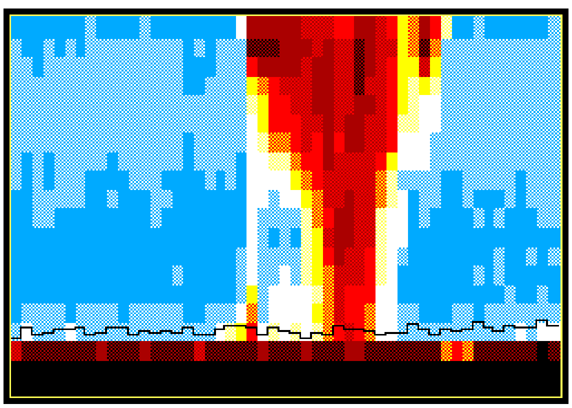


Figure 4.2.2.7 *Continuous Backscatter Profile 30m astern of the ARCO Severn, obtained on 20th August 1995. Figure clearly shows development of a small plume emanating from the draghead*

Within the limits of resolution of the ADCP™, it is estimated that the dimensions of the benthic plume at this point are less than 3m high and less than 2m wide. Similar observations were not made on any other pass close astern of any other dredgers during this campaign.

4.2.2.8 Plume Generated By The Geopotes XIV, 20th August 1995

Opportune measurements of the Geopotes XIV TSHD were made during the 20th August 1995. This is a much larger vessel than the other vessels monitored, with a hopper capacity of 7,472m^3 and maximum dredging depths of 36-42m.

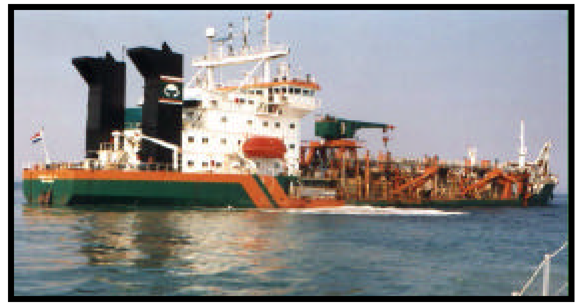


Plate 4.2.2.8 *TSHD Geopotes XIV*

The vessel loads using one or two dragheads with overspill and screened-off material discharged through a central spillway, exiting under the vessel keel. The loading rate of the Geopotes XIV is considerably greater than many other UK vessels. The plume generated by the Geopotes XIV visually appeared to have the highest SSC of the plumes observed and this was borne out by the ADCP™ data and water samples collected.

A maximum total suspended solids concentration of 2473mg/l was sampled at 80m astern of the dredger, 12m below the surface. Further samples above and below during the same vertical profile are above 1000mg/l. The silt content of sediments from these water samples was also greatest, ranging from 4% near the surface to 66% near the seabed.

Two factors must be considered with the Geopotes XIV data. In addition to the considerably higher loading rate, prospecting and reserve evaluation data suggests that the geology of the seabed where the Geopotes XIV loaded contains a higher silt content than other areas under consideration here.

Detailed analysis of the EMS output data supplied to the Crown Estate shows that the Geopotes XIV regularly lifted the draghead clear of the seabed with several interruptions to the loading process. Discussion at the time with the Master of the vessel explained this was due to the patchiness of clean (silt-free) material.

The placement in the water column of the samples which had high silt content is important. When sampled, near the seabed, silt contents of up to 58% were observed. Current velocities recorded at the time indicate an east bound flood flow of 0.30m/s.

Considering the vertical and horizontal displacement of the particles from the dredger to the point of sampling (18m and 100m respectively), the enhanced settling velocity required to reach such a position can be derived by simple trigonometry and must be of the order of 5.5cm/s. Clearly, this is far in excess of the normal settling velocity for particles of this size and further determinations are needed. It is considered unlikely that this suspension was part of the benthic plume formed by the draghead interaction with the seabed.

There is growing evidence within this study, and supported by others (*see, for example,* HR Wallingford, 1996; Whiteside *et al*, 1995), that the silt/clay fractions may have either agglomerated, attached to larger particles, or, most likely, be transported to the seabed by the formation of a density current.

The initial entry velocity of the mixtures into the water column will be important. The Geopotes XIV, by virtue of the single, central discharge point, will be more likely to demonstrate any development of a density current. Table 4.2.2.8 summarises the water sample data obtained from the Geopotes XIV plume.

Time (BST)	Transect Number	Depth (m)	Distance Astern (m)	Total Concentration (mg/l)	silts (<0.063mm) (mg/l)
14:00	-	0	136	107	n/d
14:02	-	0	115	172	n/d
14:10:41	20AU33	4	46	998	90
14:11:00	20AU33	8	77	1474	59
14:11:21	20AU33	12	80	2473	145
14:11:40	20AU33	16	84	2326	209
14:11:50	20AU33	16	98	220	128
14:14:01	20AU33	18	98	1583	16
14:14:10	20AU33	4	143	44	29
14:28:20	20AU35	4	202	135	23
14:28:48	20AU35	8	180	186	32
14:29:06	20AU35	12	150	11	4
14:29:23	20AU35	16	130	112	9
14:29:37	20AU35	18	100	74	5
14:30:34	20AU35	4	70	137	23
14:30:50	20AU35	4	42	29	n/d

Table 4.2.2.8 *Summary of suspended solids concentrations sampled from the plume developed by the Geopotes XIV, 20th August 1995. The percentage silt content is generally within the range of values expected from the prospecting data*

4.2.2.9 Plume Generated By The City Of Rochester, 21st August 1995

The development of the plume attributable to the actions of the TSHD City of Rochester whilst dredging at anchor (Plate 4.2.2.9a) has been addressed in some detail (Hitchcock & Dearnaley, 1995; Hitchcock & Drucker, 1996; HR Wallingford, 1996). However, further interpretation of the data has been undertaken, using the in-house developed software *BMAP*.

Figure 4.2.2.9 presents a *BMAP* bitmap image processed from some 16 Continuous Backscatter Profiles across the plume downstream of the anchored dredger position. Each of the three images represents the development of the plume, in terms of Acoustic Backscatter level (dB) at different levels within the water column (5m, 10m and 15m below water surface). It is clear that there is a rapid initial settlement of material (indicated by the small dark region, less than 300-500m long). Sample data indicate return to background conditions by this distance (see Table 4.2.2.9). There then follows a period where the visual boundaries of the surface expression of the plume steadily become indistinct. The ‘plume’ is only traceable using the ADCP^{TM}. Samples do not indicate suspended solids above background conditions. At 4000m downstream (corresponding to approximately 2.7 hours, the ‘plume’ is indistinguishable. Figure 4.2.2.9 also presents a selected series of the ADCP^{TM} transects used to process the bitmap image downstream of the City of Rochester. Again, clearly demonstrated is rapid initial settling of the plume sediments, “Dynamic Phase”, followed by a slower dispersion (horizontal and vertical) period, “Passive Phase”.

The track of the survey vessel, at various distances away from the dredger, is also shown.

Figure 4.2.2.9

The location of the plume, including the effects of aeration, are clearly discernible from the background, unaltered backscatter levels. It can be seen that the bulk of the plume has reached the bottom almost instantaneously, and there is little significant material still in suspension beyond 300m at the surface and 500m at 15m below the surface. This is verified by the results of the water sampling which indicated SSC returning to background levels of 5-10mg/l after similar distances. A distance of 300-500m in this instance equates to a dispersal time of 10-15 minutes since release.

Time (BST)	Transect Number	Depth (m)	Time since Discharge (@0.4m/s) (secs)	Total Concentration (mg/l)	silts (<0.063mm) * (mg/l)
11:08:07	21AU19	4	103	5	n/d
11:09:48	21AU19	8	238	9	n/d
11:11:46	21AU19	12	361	13	n/d
11:13:18	21AU19	16	482	11	n/d
11:14:50	21AU19	18	624	9	n/d
12:01:52	21AU20	4	88	69	4
12:02:20	21AU20	8	112	32	4
12:02:54	21AU20	12	131	472	3
12:03:33	21AU20	16	167	528	5
12:04:03	21AU20	18	200	505	7
12:04:03	21AU20	18	215	3	2
12:06:16	21AU20	4	338	6	1
12:24:09	21AU21	4	93	65	1
12:24:50	21AU21	8	114	340	29
12:25:20	21AU21	12	133	549	3
12:25:50	21AU21	16	163	544	6
12:26:20	21AU21	18	193	615	4
12:26:35	21AU21	18	215	490	5
12:35:35	21AU21	4	840	8	n/d
12:37:08	21AU21	8	955	8	n/d
12:38:40	21AU21	12	1050	3	n/d
12:40:10	21AU21	16	1138	2	n/d
12:41:35	21AU21	18	1223	1	n/d
13:35:25	21AU21	4	4353	2	n/d
13:37:00	21AU32	8	4548	2	n/d
13:38:30	21AU32	12	4638	2	n/d
13:40:10	21AU32	16	4738	1	n/d
13:41:40	21AU32	18	4828	2	n/d
13:43:30	21AU32	14	4938	2	n/d
15:11:45	21AU35	4	10223	0	n/d
15:13:30	21AU35	8	10328	1	n/d
15:15:06	21AU35	12	10424	1	n/d
15:16:36	21AU35	16	10484	1	n/d
15:18:36	21AU35	18	10604	2	n/d

* n/d = not determined

Table 4.2.2.9 *Summary of suspended solids concentrations sampled from the plume developed by the City of Rochester, 21st August 1995*

Plate 4.2.2.9a *TSHD City of Rochester nearly completing loading a screened cargo at anchor, English Channel, August 1995. Monitoring of the plume from this vessel indicated that suspended solids concentrations were largely returned to background levels within 300-500m downstream. Gross plume was tracked for a further 3000m.*

It is an inherent and unavoidable feature of the ADCP™ that the acoustic backscatter information from the bottom 6% of the range is corrupted by interference from acoustic side lobe returns. This effectively negates inspection of the bottom 1.1m of the water column, in 18m water depth. The contemporary concept of a benthic boundary layer plume excursion, that may well be restricted to less than 1m from the seabed, can therefore neither be refuted nor substantiated from this data and monitoring technique.

The width of the plume downstream of the dredge operation is generally less than 100m each side, reaching a maximum of 140m some 1500m downstream of the dredge vessel, beyond the limit of measurable suspended solids above background limit. At the 500m downstream position, plume width is 80m each side. Gajewski & Uscinowicz (1993) report maximum plume width of 50m each side of dredge track. This width will largely be determined by the axis of the tidal currents, turbulence and water depth.

At a distance of 400m to 600m away from the City of Rochester, the surface expression of the plume becomes less readily discernible by eye (from 3m above). Surface water transmissometer readings reduce to background levels some time before this.

Plate 4.2.2.9b shows the surface plume developed by a slightly larger dredger (TSHD Sand Harrier). Although obtained on different days using different dredgers, the scale of the plumes are largely in keeping with the proportional scale of the dredgers (the Sand Harrier is larger than the City of Rochester - 2500m^3 versus 1271m^3 respectively). Further, the Sand Harrier is dredging whilst underway (therefore dispersing the overboard returns into a greater volume of water). It may be perceived that the resultant Sand Harrier plume would be at least twice that of the City of Rochester. Scale measurements (from an incomplete photographic record) indicate that the Sand Harrier plume is somewhat less than this. At 100m astern, the plume is just 70m wide, increasing to 135m at 500m astern, where it becomes more dispersed. The turbulent nature of the overboard returns, maintaining small clouds of upwelling very fine sediments, are also clear from Plate 4.2.2.9b.

Plate 4.2.2.9b *Multiple sediment plumes formed by successive passes of the TSHD Sand Harrier. The plume is less than 70m wide, 100m astern of the dredger. Sampling data from this study would indicate that suspended solids concentrations at the far right hand side of the picture would be approaching background conditions*

4.2.2.10 Multiple Plumes Generated By The ARCO Severn, 19th August 1995 & Geopotes XIV, 20th August 1995

During the ADCP™ monitoring, the ARCO Severn (2200t) worked a course with some subsequent lines parallel and adjacent to the previous runs, rather than exactly duplicating. This gave rise to the clearly discernible “multiple plumes”, shown on Figure 4.2.2.10. This figure clearly shows the older plumes containing less suspended sediment (and other backscatterers) downstream of the present position of the dredger.

The scale of Figure 4.2.2.10 is similar to the scale of Plate 4.2.2.9a (2500m^3 TSHD Sand Harrier) obtained during a previous dredge monitoring exercise in the English Channel.

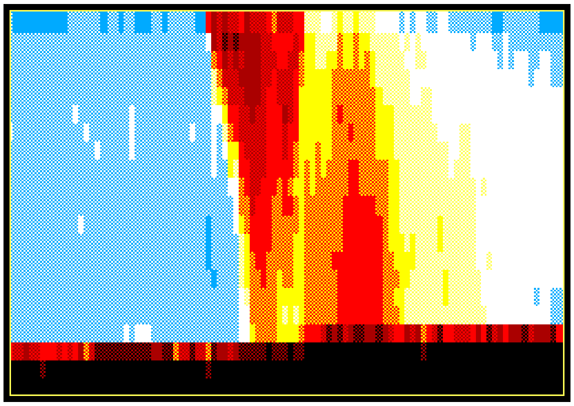


Figure 4.2.2.10 *Multiple plumes observed by Continuous Backscatter Profiling (CBP) formed by the ARCO Severn, 19th August 1995*

4.2.2.11 Plume Generated By The Geopotes XIV, 21st August 1995

A brief set of transects was obtained during the latter part of the loading period of the Geopotes XIV on the 21st August 1995. Figure 4.2.2.11 is a composite of the data obtained. An interesting observation is the first transect, obtained 88-130m astern of the dredger. This clearly shows a very ‘tight’ plume formed, with very little entrainment of sediments at the edges of the plume during the early stages of release. This reveals two things; (a) the intensifying effect of a central spillway, and (b) gives very strong support to the concept that the plume sediments settle very quickly as a density current immediately after release (the *Dynamic Phase*, Whiteside *et al*, 1995). That is to say, due to the concentrating of all overboard returns within a single central spillway, the development of a density current is virtually indisputable from the data. Interestingly, the draghead plume is not discernible at this range, although it is not known what type of draghead is fitted to the Geopotes XIV (commercially sensitive).

The next two transects again support the view that the plume settles very rapidly over the first 10-15 minutes, slowing down as it does so, such that the 4th transect reflects what is becoming known as the *Passive Phase* (Whiteside *et al*, 1995).

Horizontal dispersion is more apparent with the edges of the plume less discernible both visually at the sea surface and as identified by the ADCP™.

It must be remembered that all the while the sediments are settling to the seabed, displayed by the ADCP™ as apparently less relative acoustic backscatter, concurrently entrained air bubbles are rising to the surface and thereby also reducing the relative acoustic backscatter. The ADCP™ may therefore be considered to give a *Worst Case* representation of sediments within the water column, since some of the acoustic scatterers will not be sediments.

4.2.2.12 Overspill Samples Obtained From The ARCO Severn During The Monitoring

Overspill samples were obtained from the spillways of the ARCO Severn during the monitoring campaign. These samples have been analysed for full particle size characteristics. Table 4.2.2.12 summarises the results. The data have been divided into each cargo loaded, to identify different characteristics of each load.

The spillway samples range in suspended solids concentration from 2267-14210mg/l, averaging 6178mg/l. The total solids concentration of overspill during loading all-in is greater than during screening, although the silt content (fines <63µm) is slightly less. The fraction <63µm constitutes the majority fraction of the overspill. No particles greater than 2mm were obtained from the overspill, unlike previous sampling campaigns.

The results from these two loads are commensurate with the results obtained from other monitoring campaigns aboard the ARCO Severn (*see results of Phase One)*. Surprisingly, the data indicate only a very weak relationship between time elapsed since loading commenced and both the quantity and grade of sediments passing overboard via overspill. None of the samples from the ARCO Severn contained material greater than 2mm diameter.

	Ratio (mg/l)	% <63µm	% >63µm	% >125µm	% >250µm	% >500µm	% >1000µm
all-in	6737.69	48.10	10.60	18.95	19.69	1.83	0.51
stone	5655.06	67.84	11.31	11.78	7.82	0.69	0.55

Table 4.2.2.12 *Summary of overspill sample sediment characteristics obtained from the ARCO Severn spillways during loading of an all-in cargo (19.08.95) and screened cargo (20.08.97).*

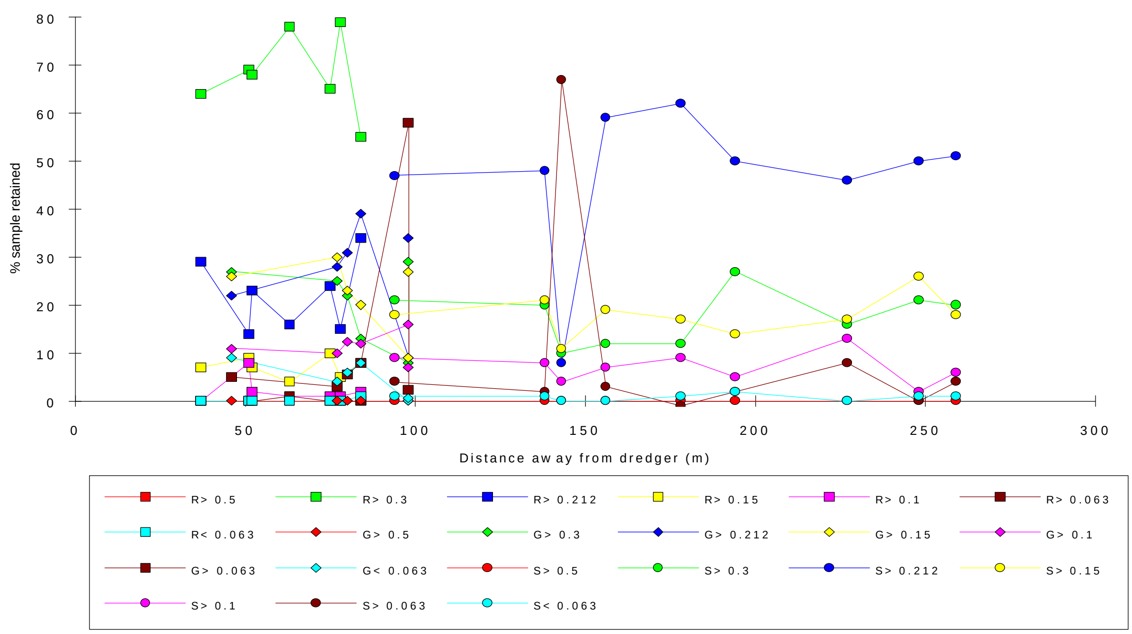
Figure 4.2.2.11

4.2.2.13 *Particle Size Distribution Of Plume Samples Obtained During The Owers Bank August 1995 Monitoring Campaign*

140 suspensate samples were obtained throughout the water column downstream of the dredger positions to characterise the plume. Geolocation of the samples in time and space has enabled calculation of minimum settling velocities based on the observed settling patterns (*see* Section 4.2.2.8). Where concentrations allow, samples have been further analysed to provide the silt/sand ratio and in some cases, full particle size analysis (Table 4.2.2.13 and Figure 4.2.2.13). The silt contents are largely within the ranges expected from the prospecting data.

Dredger	Load	Distance away From dredger	% of sample passing sieve size (mm) 0.5	0.3	0.212	0.150	0.1	0.063
Geopotes		46	100	73.33	52.38	26.67	15.24	8.89
Geopotes		77	100	75.44	47.02	16.67	7.37	4.21
Geopotes		80	100	78.36	53.33	24.31	12.41	6.26
Geopotes		84	100	76.80	52.71	27.58	16.49	8.76
Geopotes		98	100	91.61	83.01	73.98	58.49	0.00
Geopotes		98	100	70.47	36.81	10.24	2.56	0.59
Rochester	Stone	37	100	35.71	7.14	0.00	0.00	0.00
Rochester	Stone	51	100	30.68	17.05	7.95	2.27	0.00
Rochester	Stone	52	100	31.60	9.43	2.36	0.47	0.00
Rochester	Stone	63	100	21.69	5.82	1.59	1.06	0.00
Rochester	Stone	75	100	35.02	11.55	0.72	0.00	0.00
Rochester	Stone	78	100	21.03	6.15	4.10	0.51	0.00
Rochester	Stone	84	100	45.03	11.11	3.51	1.17	0.58
Severn	All-in	94	100	78.75	32.50	13.75	5.42	0.83
Severn	All-in	138	100	80.09	31.94	10.88	3.24	0.23
Severn	All-in	143	100	90.20	82.35	70.59	66.67	0.00
Severn	All-in	156	100	77.26	29.14	10.60	2.65	0.00
Severn	All-in	178	100	77.23	26.62	8.76	3.15	1.23
Severn	All-in	194	100	72.60	23.42	8.67	4.45	1.64
Severn	All-in	227	100	84.42	38.31	20.78	7.79	0.00
Severn	All-in	248	100	79.37	29.15	2.69	1.35	0.45
Severn	All-in	259	100	80.39	29.80	10.59	5.10	0.78

Table 4.2.2.13 *Particle size distribution of overspill suspensates, ARCO Severn, August 1995.*



Sieve sizes in mm Prefix R = City of Rochester G = Geopotes XIV S = ARCO Severn

Figure 4.2.2.13 *Size spectra (mm) of sediments obtained from samples within the plume downstream of three dredgers. Percentage of samples retained on sieves of sizes as indicated*

4.2.3 Discussion Of The August 1995 Owers Bank Observations

The monitoring of surface sediment plumes generated by marine aggregate dredging operations operating under normal commercial conditions and constraints has been successfully accomplished using a combination of new and traditional sampling and survey techniques. Rigorous fieldwork and post-processing procedures have been developed to ensure the maximum benefit is gained from such measurements. Considerable care and effort has been placed in developing the procedures. The monitoring team has comprised professional personnel with scientific and commercial awareness of the nature of the phenomenon to be monitored and the equipment and techniques available to do the work. The integral support of the Industry has enabled realistic appraisal of the factors governing the operations. Modification of the procedures to allow for field variations was possible.

A total of 162 Transects across the plume have been recorded using the ADCP™. Continuous Backscatter Profiling (CBP) has been shown to be fundamental to executing confident sampling programmes, with full knowledge of the suspended solids concentration minima and maxima within the plumes developed. We have developed a number of in-house programs to process and interrogate the outputs from the RDI Transect software. Equipment interfaces have been developed to facilitate the surveys. The ADCP™ transects show the bulk of the plume settling out of the water column (or, more strictly, settling to within 1.5m of the seabed) within 300 (sands) to 500m (silts) downstream. Coarse sands (> 2mm settle out virtually instantaneously). This corresponds to a time period of 10-15 minutes since release. The plume was visually discernible over a greater distance.

It was possible to track the apparent plume advecting downstream away from the City of Rochester using the ADCP™ over a distance of some 3.5km, even though for some 3km of that distance the concentrations in the plume were not significantly different to background levels (obtained from sampling and transmissometer readings). Similar results were observed, though not in as much detail, for the Geopotes XIV and the ARCO Severn. This effect is attributed to an unknown combination of the presence of minute air bubbles (nearer the dredger than in the far field), bio-chemical precipitates and/or organic material entrained and vigorously disaggregated before return to the water column during the dredging operation.

It is possible from the biological data reviewed (*see* Section 6) and from field observations of trawling activity behind dredgers, that the negative impact is largely limited to an aesthetic impact, with little impact imposed on the surrounding biological communities. Enhancement of feeding opportunities and protection from predation may be a positive effect of the extended plume component. Further investigation is required and is discussed in Section 4.4.

The contemporary concepts of the development of Dynamic and Passive Phases during the plume generation and decay are strongly supported. The evidence for the development of density currents during the Dynamic Phase and their importance is compelling. Settling velocities for silt have been calculated to be of the order 17-55mm/s (compared with more standard 0.1-1.0mm/s). Interestingly, more reasonable and comparable figures for sands are derived (circa 30-60mm/s). It is postulated that the figures for silts are, in effect, a preliminary determination of the settling velocity of the density current formed during the initial Dynamic Phase. It is reasonable to expect that, given more data obtained closer to the dredge vessels (less than 500m range), higher settling velocities may be encountered under certain conditions. Further, it is suggested that significant particle agglomeration occurs with the sediments settling as particle assemblages having settling velocities substantially higher than the individual member particles. Whilst more determinations of these settling rates are required, importantly this shows the possible hazards inherent in the application of a single particle settling velocity within models of suspended sediment plumes arising from dredging operations.

The vertical velocity component recorded by the ADCP™ is presently being investigated by the author as a further source of information on the magnitude of the downward plume velocity in the initial stages when entry velocity into the water column from the vessel will be significant. Figure 7.3 records the upward (positive) and downward (negative) velocity components 80m astern of the dredger. The central region of the figure clearly shows a downward water body velocity of some 15-20cm/s with corresponding upwelling at both margins of similar magnitude. Further investigation is required to determine the utility of such data.

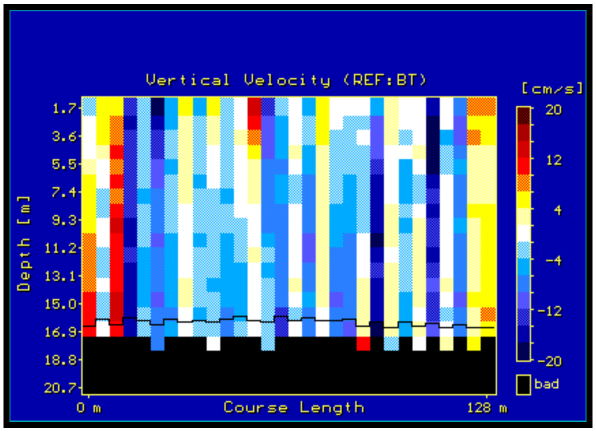


Figure 7.3 *Vertical velocity component 80m astern of the ARCO Severn, 21 August 1995. Positive figures are upward velocity; negative figures are downward velocity. Other than at both margins of the transect, there is a general downward velocity of some 10-15cm/s within the plume. 'Upward' water movement may be due to rising air bubbles. The comparative relative backscatter for this transect is shown as Transect One of Figure 7.2.9.*

Detailed analysis of the mineralogy of the sediments at the dredged sites has not been determined. It is known that the presence of the clay mineral montmorillonite enhances the flocculation of the fine particles. To what extent this may explain the difference between the plume excursion in different (in the geological sense) licence areas is not clear.

The benthic plume was clearly identified on only one of 162 CBP Transects recorded astern of the three dredgers monitored. Samples were not obtained from within the benthic plume. It is evident that the benthic plume is quite small in comparison to the surface plume and is rapidly engulfed by the rapidly descending density current.

The following section investigates the development of the benthic plume at and just above the seabed through novel use of underwater cameras and imaging combined with water sampling and concurrent ADCP profiling from an attendant survey vessel in a separate field campaign.